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EFFECTIVENESS OF PASSIVE DEVICES IN ALLEVIATION OF FLOW-INDUCED OSCILLATIONS OF THE NOZZLES OF A MULTI-BOOSTER LAUNCH VEHICLE

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ABSTRACT

Wind tunnel tests to quantify the flow induced oscillations of nozzles of strap-on boosters of a typical launch vehicle have been performed under jet-off conditions in the Mach number range 0.8 to 2.5. The effects of gymballing the nozzles on the steady and unsteady radial and tangential moments acting at the simulated position of gymbal actuators have been studied. The loads are seen to increase as the gymbal angle increases. The effectiveness of various load alleviating passive devices in reducing steady and unsteady loads was evaluated. The most effective device was found to be a semi-circular segment. The spectra of unsteady moments indicate that the loads alleviating devices do not significantly alter the magnitude as compared to that of the baseline data.

Key words: Flow induced oscillations, Fluid-structure interactions, Unsteady aerodynamics

NOMENCLATURE

f_n	Natural frequency of the nozzle, the actuator and associated structural elements
f_R	Reduced frequency corresponding to the model scale
F_R	Radial aerodynamic force
F_T	Tangential aerodynamic force
M	Free-stream Mach number
M_R	Radial moment at the simulated location of gymbal actuator on the nozzle
M_T	Tangential moment at the simulated location of gymbal actuator on the nozzle
G	Gymbal angle
α	Angle of attack of the model

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1. INTRODUCTION

Liquid rocket engines usually have gymballed nozzles for purposes of thrust vector control to facilitate the control of the trajectory. The nozzles are normally located at the base of the rocket, subjecting the nozzle to the relatively low energy near-wake flow of the rocket. However, when the nozzle is deflected, a part of the nozzle occurs in the outer (potential) flow, causing reattachment of the separated shear layer from the base of the rocket on to the nozzle. The reattachment point being unsteady, the nozzle, its actuators and associated linkages are subjected to a flow-induced oscillation, even in the absence of the jet exhaust. As the rocket accelerates, the problem becomes more complicated, with occurrence of unsteady shock waves, viscous interactions, etc. In the presence of a jet exhaust, the shear layer reattachment is governed by the pressure ratio of the jet exhaust as well, in addition to other parameters. Wind tunnel tests in the absence of jet exhaust are considered sufficient to quantify the forcing function and the response due to the reattaching flow.

In a typical launch vehicle featuring multiple strap-on boosters, f_n is quite low, corresponding to the rigid body modes. The presence of discrete frequencies (especially low frequencies) in the forcing function must therefore be identified to avoid increasing amplitudes of flow-induced oscillations. In the present studies, f_R chosen to be greater than 800 Hz so that the nozzle has a flat frequency response in the region of interest. Since the transfer function between the forcing function and the response is constant till the resonance condition is approached, any discrete frequency in the forcing function would appear in the response signal as well. Further details of the technique are given in Ref. 1. In the present work, the effect of nozzle gymballing on the steady and unsteady response is presented. The effect of few passive ad-on devices on the steady and unsteady response is quantified.

2. MODEL DETAILS

The test object is a scaled model of a typical launch vehicle featuring four strap-on boosters surrounding a central core vehicle, as shown in Figure 1.

Figure 1 Photograph of the model

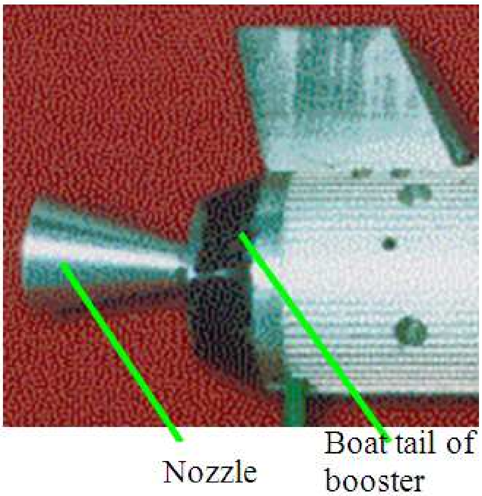


Figure 2. Aft portion of one of the boosters

Each of the four strap-on boosters is provided with a nozzle, canted 6° radially outwards. While two of the nozzles are rigidly held (not instrumented) inside the boosters, the other two are designed as flexible cantilevers, with the roots rigidly held inside the boosters. Six interchangeable pairs of nozzles, three rigid and three flexible, were specially designed and fabricated. Figure 2 shows a photograph of one of the boosters

3. TEST FACILITY

The tests were conducted in the 1.2m trisonic wind tunnel at the National Aerospace Laboratories, Bangalore. The tunnel is an intermittent blowdown type facility with a 1.2m x 1.2m test section and Mach number capability from 0.20 to 4.0. Supersonic Mach numbers are achieved in the test section by variation of contour using a flexible nozzle; transonic Mach numbers are achieved using a transonic insert which features perforated walls. The top and bottom walls have 0.5” diameter inclined holes with 6% open area ratio. The side walls have 0.5” diameter normal holes with 20% open area ratio. Acoustic baffles are used in the plenum chamber of the transonic insert to reduce unsteady pressure fluctuations in the test section. The model incidence may be varied in the range –15° to 27° continuously or in steps during a run; the model can be rolled and locked from 0° to 360° prior to a run. More details of the facility are given in Ref. 2. To quantify the steady and unsteady loads, three pairs of flexible nozzles, with gymbal angles of 0°, 4° and 8° were tested. The end-views of 0°and 8° the nozzles are illustrated in Figure 3.

4. TEST DETAILS

The tests were carried out in the Mach number range 0.80 to 2.5 and in the α-range of $\pm 4^\circ$ in 2° steps. The test Reynolds number (based on the booster diameter) was varied in the range 1.1 to 1.3 million.

5. RESULTS AND DISCUSSSIONS

5.1 Effect of Gymbal Angle

For a physical understanding of the forcing function, the flow pattern on the nozzle (Figure 4) for a gymbal angle of 0° may be examined. Reattachment of the separated shear layer from the booster is clearly seen. When the gymbal angle is increased, a greater portion of the nozzle is exposed to the outer flow. Consequently, the nozzle is expected to experience changing aerodynamic loads along radial (F_R) and tangential (F_T) directions with respect to the core vehicle, as shown by the arows in Figure 3. However, the magnitude of the loads depend on the position of the nozzle (whether in the pitch-plane or in the yaw-plane, angle of attack, Mach number, etc).

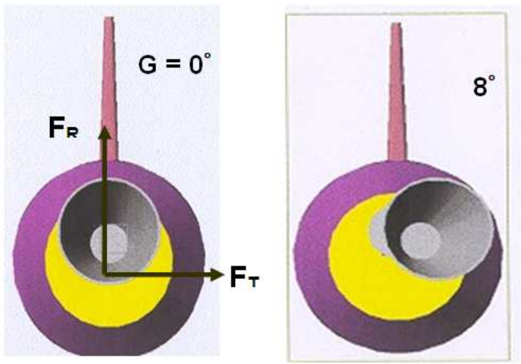


Figure 3. End view of gymballed nozzles

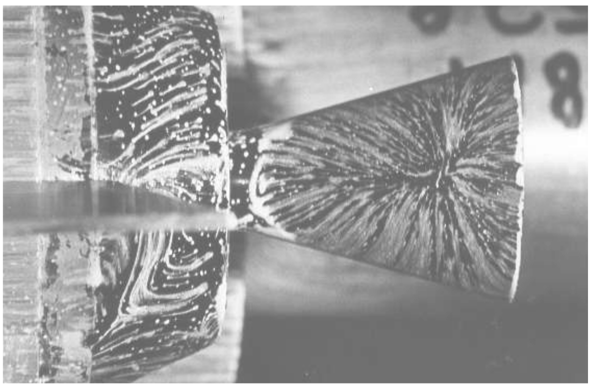


Figure 4. Typical reattached flow on the nozzle with 0° gymbal (Ref. 1)

Consequent to these forces, the flow-induced moments (M_R and M_T) acting at the location of the gymbal actuator on the nozzle also vary. Figure 5 and 6 show typical steady values of M_T on the pitch plane and yaw-plane nozzles respectively, at M = 1.80 and $\alpha = 0^\circ$. Figure 7 and 8 show the spectra of M_R and M_T fluctuations on the pitch plane nozzle at M = 1.80. It is seen from these plots that even though the magnitude of moments shows an increasing trend with the gymbal angle, the spectra of fluctuations do not show such a monotonic behaviour. Interestingly, while no discrete frequencies are seem in M_R up to 600 Hz, discrete frequencies of 446 Hz and 466 Hz are indicated in M_T. These frequencies appear to be flow-induced. However, the magnitude at these frequencies are quite low.

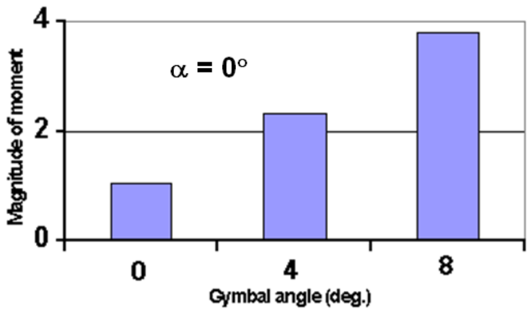


Figure 5. Effect of gymbal angle on M_T for the pitch- plane nozzle at M = 1.80

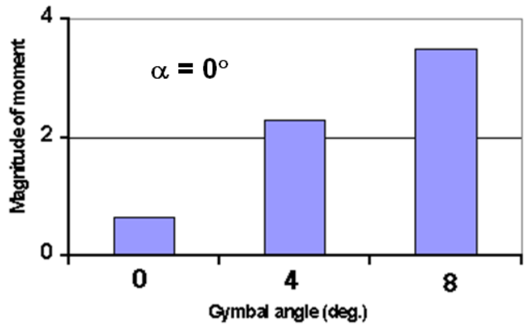


Figure 6. Effect of gymbal angle on M_T for the yaw- plane nozzle at M = 1.80

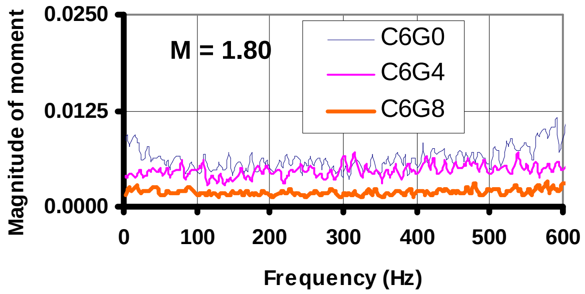


Figure 7. Effect of nozzle gymballing on spectra of moment (M_R) fluctuations of (pitch-plane nozzle)

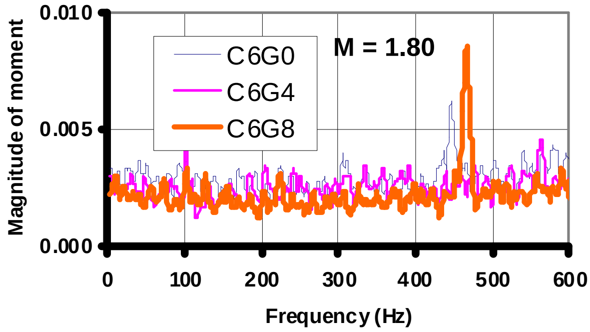
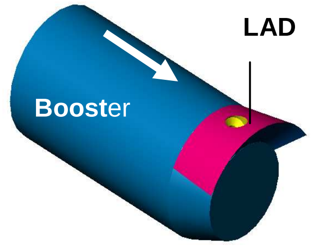


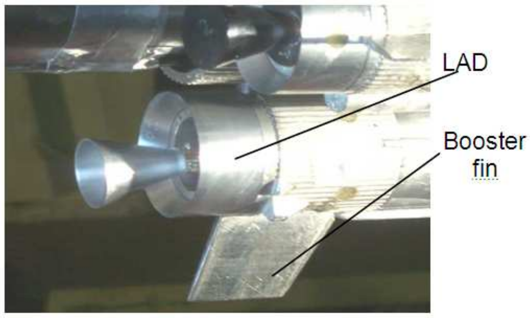
Figure 8. Effect of nozzle gymballing on the spectra of moment (M_T) fluctuations of pitch- plane nozzle)

5.2 Effect of Load Alleviation Device (LAD)

It is seen from the surface-flow patterns (Figure 3) that the forcing function responsible for the unsteadiness is the reattachment of the separated shear layer from the booster boat-tail on the nozzle. Therefore, any device, which either delays or prevents the reattachment, may be expected to alleviate the flow-induced loads. However, the effectiveness of the device would depend on the nozzle gymbal angle, the local flow conditions, Mach number, etc. It is noted from Figs. 5 and 6 that the maximum steady loads occur when G = 8°, i.e., when the area of the nozzle exposed to the outer flow is maximum. The LAD, which alleviates the loads when G = 8° may therefore be expected to alleviate loads under all conditions. Figure 9 shows typical views of two LAD's assembled on the aft portion of a booster. As shown in Figure 9 (a), one of the LAD's is a segment mounted over a part of the boat tail at the booster base. The length of the segment and the included angle are the parameters. Figure 9 (b) shows a 360° segment, i. e., a circular ring. Results from wind tunnel tests on the model with G = 8°, for the baseline (no LAD), Segment 1 (150° x 20mm), Segment 2 (180° x 20mm) and Segment 3 (360° x 20mm) are discussed below:

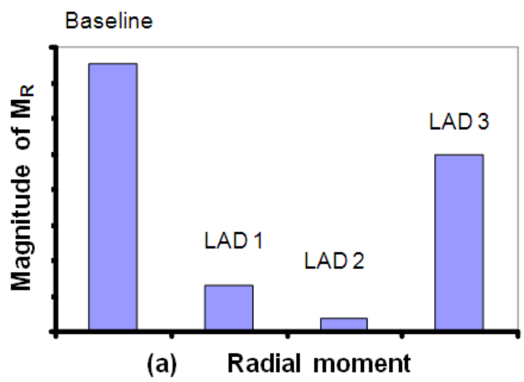


(a) LAD segment; 150° x 20 mm



(b) LAD cylinder; 360° x 20

Figure 9. Typical Load Alleviation Devices attached to the base of the booster



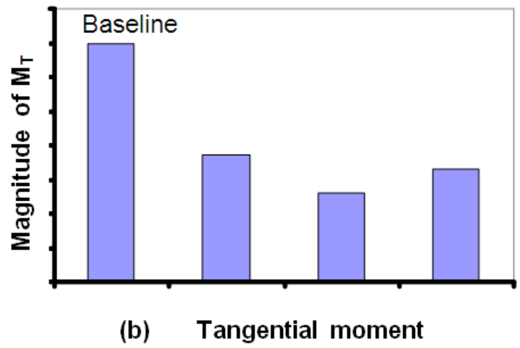


Figure 10. Effectiveness of LAD's on pitch plane nozzle

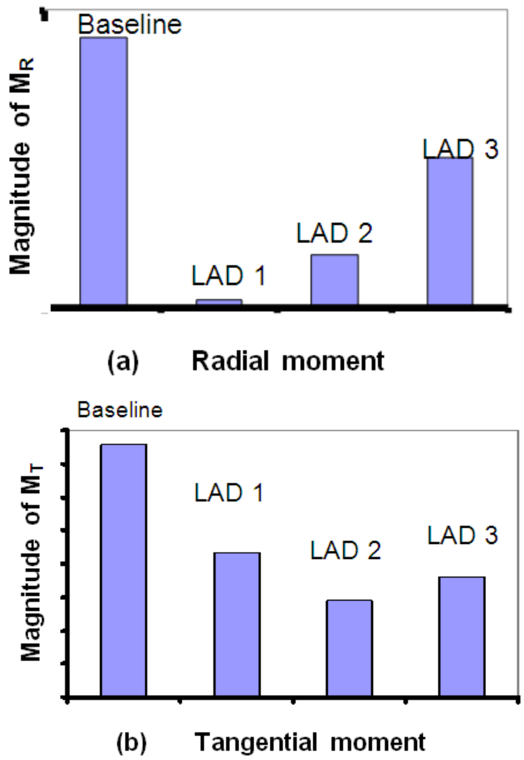


Figure 11. Effectiveness of LAD's on yaw plane nozzle

Figures 10 and 11 show the mean value of M_R and M_T, for the pitch-plane and yaw-plane nozzles respectively. From these figures, it is noted that all the LAD's show reduction in the mean values of both the radial and tangential moments. However, the reduction achieved in the radial moment is more than that in the tangential moment. This is to be expected since the LAD alters the position of shear layer reattachment directly in the radial plane. Even though LED 1 and LED 2 indicate maximum effectiveness for the nozzle with G = 8°, when the results from all the gymbal angles and LAD's are examined, LAD 2, which is a segment of 180° and 20mm length appears most effective in reducing the mean moments of both the pitch and yaw-plane nozzles.

Figures 12 and 13 show the spectra of M_R and M_T for the pitch plane nozzle at M = 1.80 and α = 0° for the nozzle with G = 8°. The results clearly indicate that the LAD's do not modify the unsteady loads significantly. Interestingly, in the M_T spectra, a discrete frequency around 470 Hz, induced by the flow is observed, where as no discrete frequency is seen the spectrum of MR. However, the magnitude of the moment at this frequency is small.

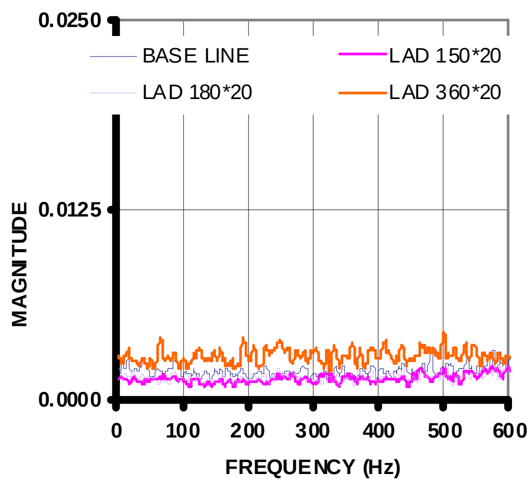


Figure 12. Spectra of MR for the pitch plane nozzle

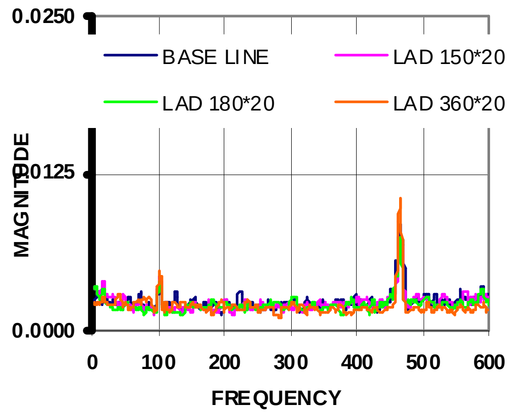


Figure 13. Spectra of M_T for the pitch plane nozzle

6 CONCLUSIONS

Wind tunnel tests to quantify the flow induced oscillations of nozzles of strap-on boosters of a typical launch vehicle have been performed under jet-off conditions in the Mach number range 0.8 to 2.5. The effects of gymballing the nozzles on the steady and unsteady radial and tangential moments acting at the simulated position of gymbal actuators have been studied. The loads are seen to increase as the gymbal angle increases. The effectiveness of various load alleviating passive devices in reducing steady and unsteady loads was evaluated. The most effective device was found to be a semi-circular segment. The spectra of unsteady moments indicate that the loads alleviating devices do not significantly alter the magnitude.

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2 1.2m Wind Tunnel Users’ Manual, NTAF, NAL.